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THERMOCHEMICAL EROSION MODELING OF THE 25-MM M242/M791 GUN SYSTEM

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13. ABSTRACT *(Maximum 200 words)*

The MACE gun barrel thermochemical erosion modeling code addresses wall degradations due to transformations, chemical reactions, and cracking coupled with pure mechanical erosion for the 25-mm M242/M791 gun system. This predictive tool provides gun system design information that is otherwise impractical. The nitrided A723 and 0.002-inch plated chromium/A723 wall materials are evaluated for erosion using the M242 Cycle A firing scenario. This complex computer analysis is based on rigorously evaluated scientific theory that has been validated in the rocket community over the last forty years. Our gun erosion analysis includes the standard interior ballistics gun code (XNOVAKTC), the standard nonideal gas-wall thermochemical rocket code modified for guns (CCET), the standard mass addition boundary layer rocket code modified for guns (MABL), and the standard wall material ablation conduction erosion rocket code modified for guns (MACE). This analysis provides wall material erosion predictions and comparisons (ablation, conduction, and erosion profiles) as a function of time, travel (customer-selected 6-inch, 12-inch, 30-inch), and number of rounds to barrel condemnation. These M242/M791 gun system predictions agree well with the standard wall heat transfer/temperature profile code (FDHEAT) and actual measured gun system erosion data.

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INTRODUCTION

The study of chemical reactions in flow systems (aerothermochemistry) was first described by von Karman in 1951 (ref 1). The modification of the heat transfer coefficient (blocking) for the mass addition of chemically reacting wall material into the boundary layer was first described by Reshotko and Cohen in 1955 (refs 2,3). The thermochemical erosion of reentry vehicle heat shield material for various chemically reacting systems was first studied by Denison and Dooley in 1957 (ref 4). This thermochemical erosion theory was unified/summarized by Lees of CalTech and The Ramo-Wooldridge Corporation in 1958 (ref 5). The near exclusive use of Lees' now JANNAF standardized model (refs 6-8) has stood the test of time and demonstrates that the major assumptions are still reasonable and valid.

Gun barrel technology has focused on reducing mechanical/metallurgical gun barrel failures with great success, while gun barrel gas-wall thermochemical/thermal ablation coupled with aerodynamic flow erosion has intensified due to performance requirements demanding the use of high-flame temperature propellants. Practical gun barrel design should address thermochemical and thermal ablation, although the latter constitutes a poor design since the proximity of the wall solidus temperature should be avoided.

In 1992, after an exhaustive search, the U.S. Army Benet Laboratories (Benet) teamed with Software and Engineering Associates (SEA) to successfully modify the JANNAF standard rocket erosion codes (TDK/MACE) (refs 6-9) into the first comprehensive gun barrel thermochemical erosion modeling code that addresses wall degradations due to thermal (transformations), thermochemical (reactions), and thermomechanical (cracking) effects coupled with pure mechanical erosion (high-speed flow, wear). SEA is the sole maintainer and developer of these rocket erosion codes. The compressible chemical equilibrium and transport (CCET) thermochemistry code is similar but much more robust than the nonideal gas thermochemical equilibrium (BLAKE) code (ref 10). The gun erosion analysis uses standard interior ballistics gun code (XNOVAKTC) (ref 11) core flow data as input. In 1993, a joint SEA/Benet gun erosion workshop was held to introduce this code to the gun community (ref 9). Many ADPA Tri-Service sponsored gun erosion meetings have implied a thermochemical erosion mechanism for various gun systems including the M242/M791 gun system (refs 12,13). U.S. Army experimental data support the existence of gun barrel oxidation (ref 14). In July 1995, Benet and SEA jointly published (AIAA) the first known comprehensive gun barrel thermochemical erosion modeling code (ref 15).

THEORY AND PROCEDURE

This report models the 25-mm M242/M791 gun system with its HC-33 propellant and 3200°K flame temperature (ref 12).

The M242/M791 gun system (ref 12) erosion analysis includes the following codes:

- Standard interior ballistics gun code (XNOVAKTC for core flow) (ref 11)
- Standard nonideal gas-wall thermochemical rocket code modified for guns (CCET for gas-wall transport/chemistry) (refs 6,8,9)
- Standard heat transfer modified by mass addition to boundary layer rocket code modified for guns (MABL for transport and cold/adiabatic wall properties) (refs 6,9)
- Standard wall material ablation conduction erosion rocket code modified for guns (MACE) (refs 7,9)

The XNOVAKTC code and its core flow output are well known to the gun community; see Reference 11 for further information.

The CCET code (refs 6,8,9) outputs gun system inert/reacting gas-wall enthalpy (H_{gw}), condensed phase products mass fraction (C_{cg}), and ablation potential (B_a) data as a function of pressure and temperature. Combustion product omissions and gas-wall reactivity are based on in-house experimental testing, proprietary communications, and a U.S. Army report (refs 9,14). The CCET code assumes that as the gas diffuses to the wall, it reacts to form products as follows:

$$B_a = (C_w - C_{cg})/C_g \tag{1}$$

where C_w is the mass fraction of wall material and C_g is the mass fraction of the gas edge (ref 9).

The MABL code (refs 6,9) outputs adiabatic wall recovery enthalpy (H_r) and adiabatic wall temperature (T_{aw}) data as a function of time and travel. The recovery enthalpy is the potential chemistry driver where the heat transfer approaches zero and the adiabatic wall temperature is the potential temperature without reactions. The MABL code also outputs cold wall heat transfer rate (Q_{cw}) data as a function of time and travel. This heat transfer rate is the wall heat flux evaluated at the cold wall temperature. The MABL code heat and mass transfer model includes the following three equations. The first equation is for mass addition to the boundary layer, the second equation is for heat-to-mass transfer ratio, and the third equation is for the overall correlation between the first and second equations:

$$r_e\, U_e\, Ch_o = Q_{cw}/(H_r - H_{gw}) \tag{2}$$

$$r_e\, U_e\, Ch_b = Mdot_g/B_a;\; Le = 1 \tag{3}$$

$$Ch_b/Ch_o = f(B_a, M_w) = 1 - (h\, Mdot_g/r_e\, U_e\, Ch_o) \tag{4}$$

where r_e is edge density, U_e is edge velocity, Ch_o is Stanton number without blowing, Q_{cw} is cold wall heat transfer, H_r is recovery enthalpy, H_{gw} is gas-wall enthalpy, Ch_b is Stanton number with blowing, $Mdot_g$ is gas mass transfer, Le is Lewis number, B_a is ablation potential, M_w is molecular weight, and h is $f(G\text{-}BL$ molecular diffusion) (ref 9).

The MACE code (refs 7,9) calculates the actual transient thermochemical response and generates wall material erosion predictions and comparisons (ablation, conduction, and erosion profiles) as a function of time, travel (customer-selected 6-inch, 12-inch, 30-inch), and number of rounds to barrel condemnation. The nitrided A723 and 0.002-inch plated chromium/A723 wall materials are evaluated for maximum wall temperature and erosion using the M242 Cycle A firing scenario. The MACE code can do any propellant-gun barrel combination on a high end PC; each mechanism's importance is identified and incremental upgrades are feasible.

The M242/M791 MACE maximum wall temperature gun system predictions are compared to those of the U.S. Army's standard gun barrel finite difference heat transfer code (FDHEAT) (ref 16) that calculates the transient temperature distribution in a multilayered cylinder and models radial/axial heat flow separately. The nitrided A723 and 0.002-inch plated chromium/A723 wall materials are evaluated by FDHEAT for maximum wall temperature using the M242 Cycle A firing scenario. The M242/M791 gun system predictions are also compared to actual M242/M791 nitrided A723 experimentally-measured gun system erosion data.

RESULTS AND DISCUSSION

Figure 1 provides a gun erosion modeling overview that includes the bore surface erosion analysis using the ABAQUS, XNOVAKTC, CCET, MABL, and MACE codes. In addition, this figure provides an overview of the subsurface erosion analysis using metallographic data and the XNOVAKTC, CCET, MABL, and MACE codes.

Figure 2 gives the calculated ambient temperature-conditioned 25-mm M242/M791 XKTC data for gas velocities (V), gas temperatures (T), and gas pressures (P) as a function of time for the customer-selected axial positions 6, 12, and 30 inches from the rear face of the tube (RFT).

Figure 3 gives the calculated ambient temperature-conditioned 25-mm M242/M791 MABL data for recovery enthalpies (H_r) and cold wall heats (Q_{cw}) as a function of time for the same customer-selected axial positions above. The data in Figure 3 are two of three parts of the driving potential ($Q_{cw}/(H_r\text{-}H_{gw})$), which is essentially mass affected per unit area per unit time.

Figure 4 gives the calculated 25-mm M242/M791 CCET data for reacting wall enthalpies (H_w) and ablation and melting potential (B_a) for high contraction (HC) chromium and nitrided A723 as a function of temperature. The data in the left plot of Figure 4 consist of the third of three parts of the driving potential ($Q_{cw}/(H_r\text{-}H_{gw})$) , which again is essentially mass affected per unit area per unit time. Figure 4 shows that HC chromium metal oxidizes at 3600°R (3110°F), it melts at 3830°R (3340°F), and its oxide melts at 4570°R (4080°F). The figure shows that nitrided A723 steel oxidizes at 1900°R (1410°F), its oxide melts at 2960°R (2460°F), and it melts at 3250°R (2760°F). The nitrided A723 wall oxidizes substantially below its metallic melting point, while the HC chromium wall oxidizes just below its metallic melting point. The nitrided A723 wall has an expansive flaking oxide that enhances further oxidation, while the HC chromium wall has a passivating oxide that prevents further oxidation. The nitrided A723 wall oxide melts well below its metal, while the HC chromium wall oxide melts well above HC chromium metal.

Figure 5 shows the calculated 25-mm M242/M791 MACE surface/subsurface exposure and flow modeling for the 6-inch from RFT axial position. The upper part of this figure shows the first 0.002-inch nitrided A723 steel with 100 percent of the A723 surface exposed for thermochemical ablation. The lower part of this figure shows the 0.002-inch HC chromium plate over the first 0.002-inch A723 with its 0.0070-in.^{2} average HC chromium plates and 0.0005-inch average crack widths. For the last 90 percent of the gun's life, 12 percent of the A723 subsurface is exposed for thermochemical ablation.

When a pair of 0.0035-inch wide average A723 degraded voids occurs below adjacent HC chromium crack bases, metallography and modeling tell us that the 0.0070-in.^{2} chromium plate spalls and it should be noted that about half the area under the plate is consumed. Specifically, when sufficient FeO is formed at the chromium/A723 interface but fails to melt, FeO occupies a larger volume than the original Fe, pushes up the chromium platelet from all four sides, eventually a planar crack propagates across the interface, and the chromium platelet spalls. If FeO is formed at the chromium/A723 interface and melts, then a much faster spalling action occurs. Variation of exposed area of subsurface A723 varies its Q_{int}, T_{int}, and driving potential (Q/dH). Cyclic thermal-induced evolution of mainly H_2O, O_2, H_2, and Cl_2 gives HC chromium shrinkage and heat-check cracking. HC chromium achieves "maximum" shrinkage/cracking at about 10 percent of the gun's life for M791 rounds using the Cycle A firing scenario. A723 thermochemical gas wash at heat-checked crack bases and after platelet spalling enhances mechanical pitting and chipping.

Figure 6 gives the calculated MACE ambient temperature-conditioned 25-mm M242/M791 maximum wall and interface temperatures as a function of rounds for the 150-round Cycle A and single-shot firing scenarios. In order of decreasing maximum wall and interface temperature, the six curves given in this figure are for:

- Bare A723 steel after the Cycle A firing scenario (CA)
- HC chromium plate after the Cycle A firing scenario
- Chromium/A723 interface after the Cycle A firing scenario

- Bare A723 steel after a single-shot scenario (SS)

- HC chromium plate after a single-shot scenario

- Chromium/A723 interface after a single-shot scenario

The highly verified FDHEAT code (ref 16) is considered the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) standard code for wall temperature predictions, and all respective MACE data are within 100°F of the corresponding FDHEAT data.

As noted in Figure 6, the following are above 2400°F and do not pertain to the presented data: iron oxide melting point, A723 melting point, HC chromium temperature of reaction, HC chromium melting point, and chromium oxide melting point. HC chromium is thermochemically inert at 6, 12, and 30 inches from RFT for both the Cycle A and single-shot firing scenarios. Bare A723 steel and the chromium/A723 interface are thermochemically reactive at the same RFT positions for the Cycle A firing scenario, since they exceed the A723 temperature of reaction. Bare A723 steel is thermochemically reactive at 6 and 12 inches from RFT; it is thermochemically inert at 30 inches from RFT for the single-shot firing scenario, since only the first two positions exceed the A723 temperature of reaction. The chromium/A723 interface is thermochemically inert at all three RFT positions for the single-shot firing scenario, since none of these positions exceeds the A723 temperature of reaction.

Figure 7 gives the calculated MACE ambient temperature-conditioned 25-mm M242/M791 cumulative wall erosion-to-condemnation as a function of M791 rounds. As highlighted, the 25-mm M242 gun erosion condemnation occurs when A723 gas wash first exceeds 0.020-inch at any location. Also highlighted, A723 gas wash onset is at 0.002-inch and as the interface degrades, then the chromium plate begins spalling platelets forming pits.

The left-most of the two curves in Figure 7 shows that for the typical M791, nitrited A723 at 6 inches from RFT achieves erosion condemnation at 4000 rounds. This agrees to within 10 percent of the number of rounds given in the M242/M791 gun system technical data package (ref 12). In the gun life, nitrided A723 is uneroded at 12 and 30 inches from RFT. The right-most of the two curves shows that for the typical M791, HC chromium plate/A723 at 6 inches from RFT achieves A723 gas wash onset at 4200 rounds and erosion condemnation at 8200 rounds. If HC chromium chips, A723 erosion begins at that round number. In the gun life, HC chromium is uneroded at 6, 12 and 30 inches from RFT, and the A723 interface is uneroded at 12 and 30 inches from RFT despite HC chromium chipping.

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Figure 1 - Gun Erosion Modeling Overview

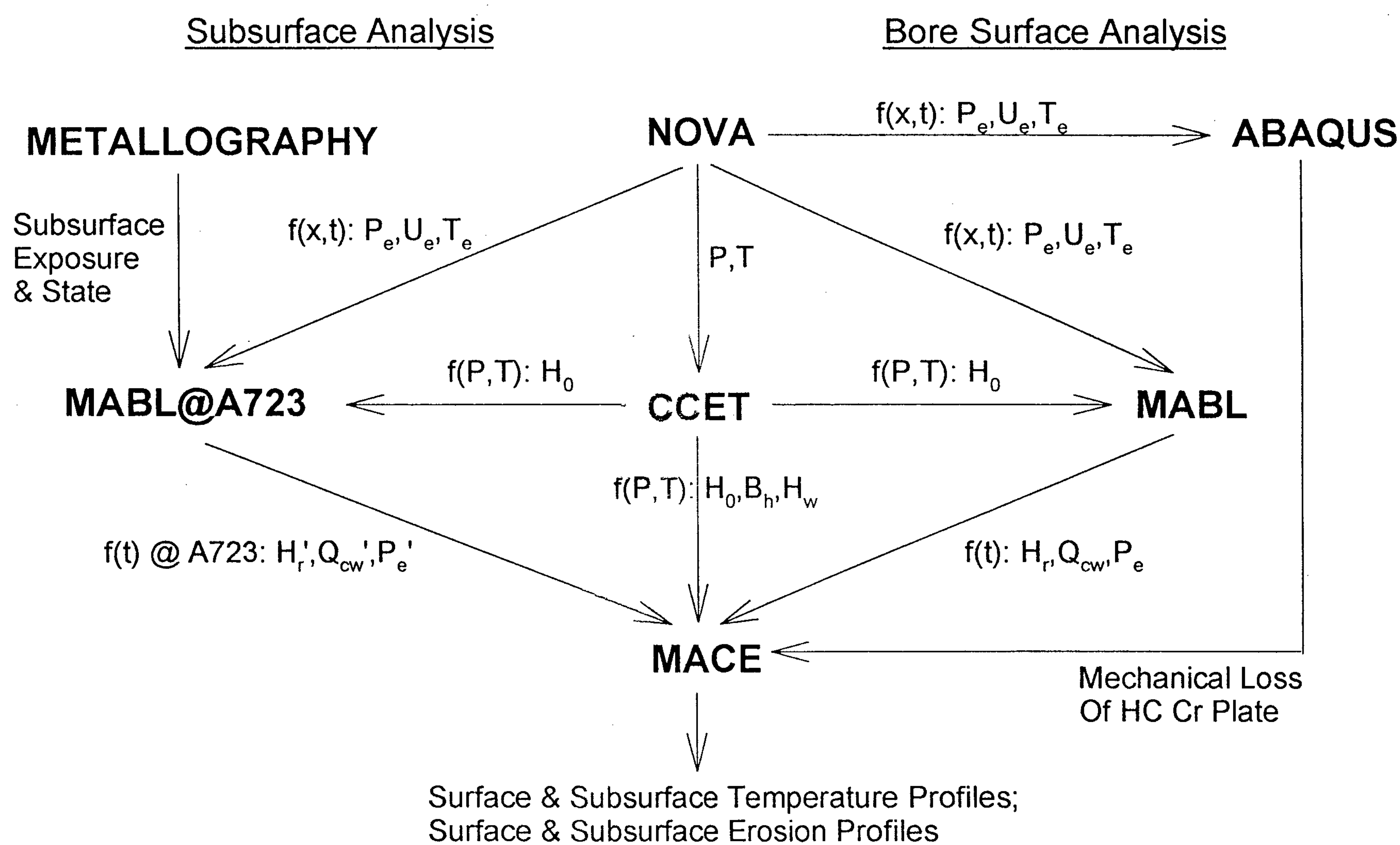


Figure 2 - Ambient Conditioned 25mm M242/M791 XKTC Data

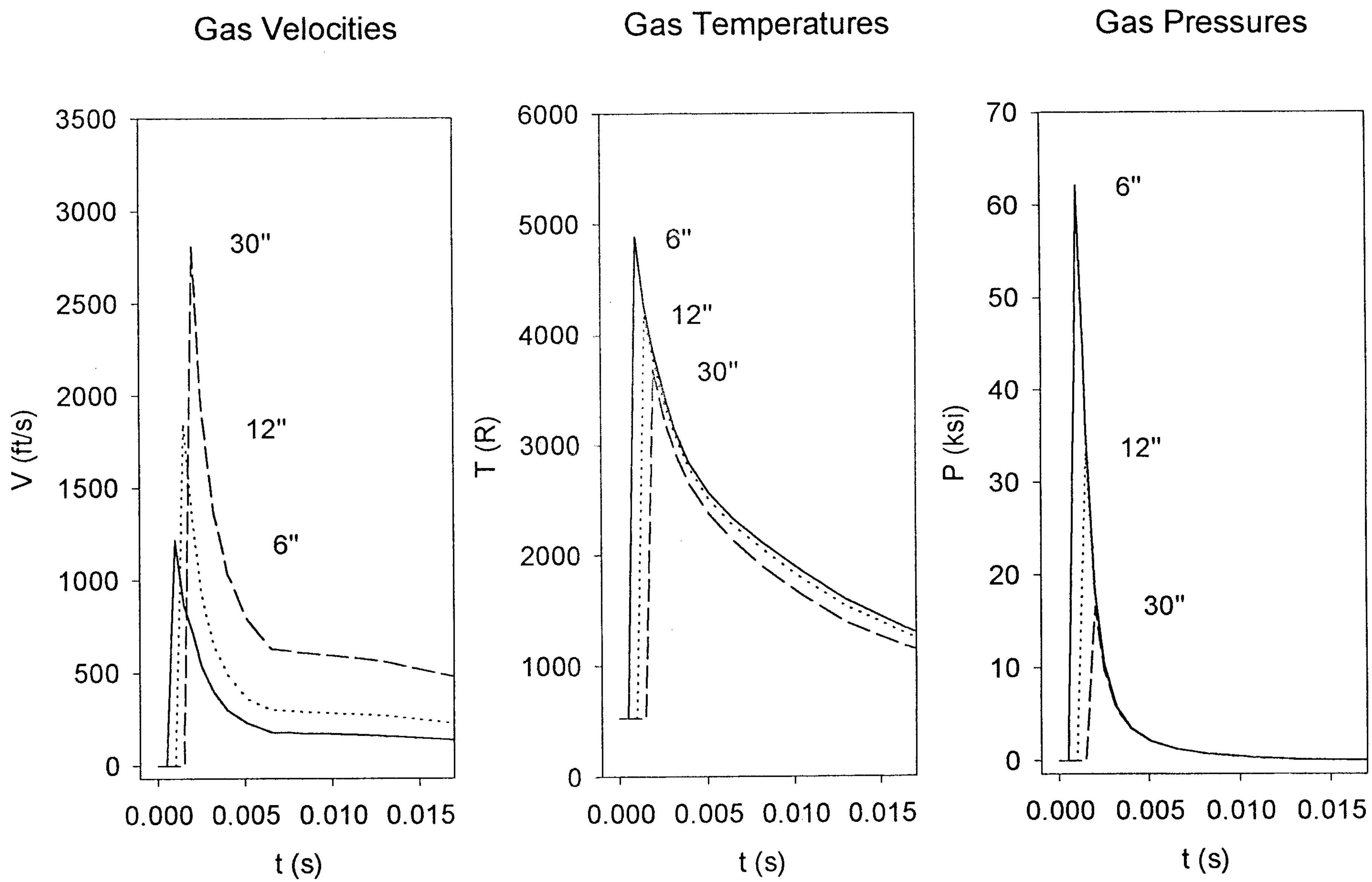


Figure 3 - Ambient Conditioned 25mm M242/M791 MABL Data

(Qcw / (Hr-Hgw) = Mass Affected / Area Time = Driving Potential)

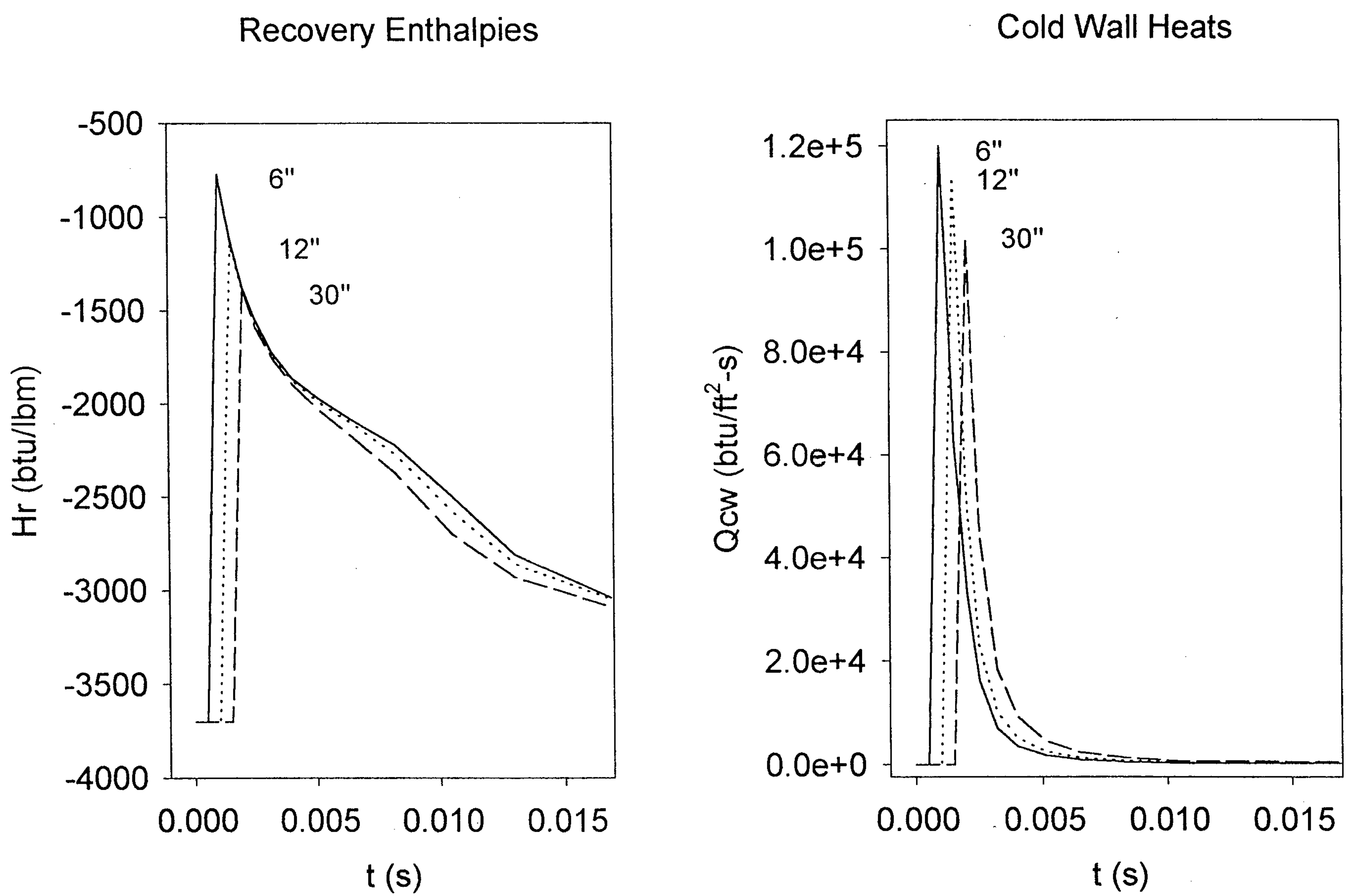


Figure 4 - 25mm M242/M791 CCET Data

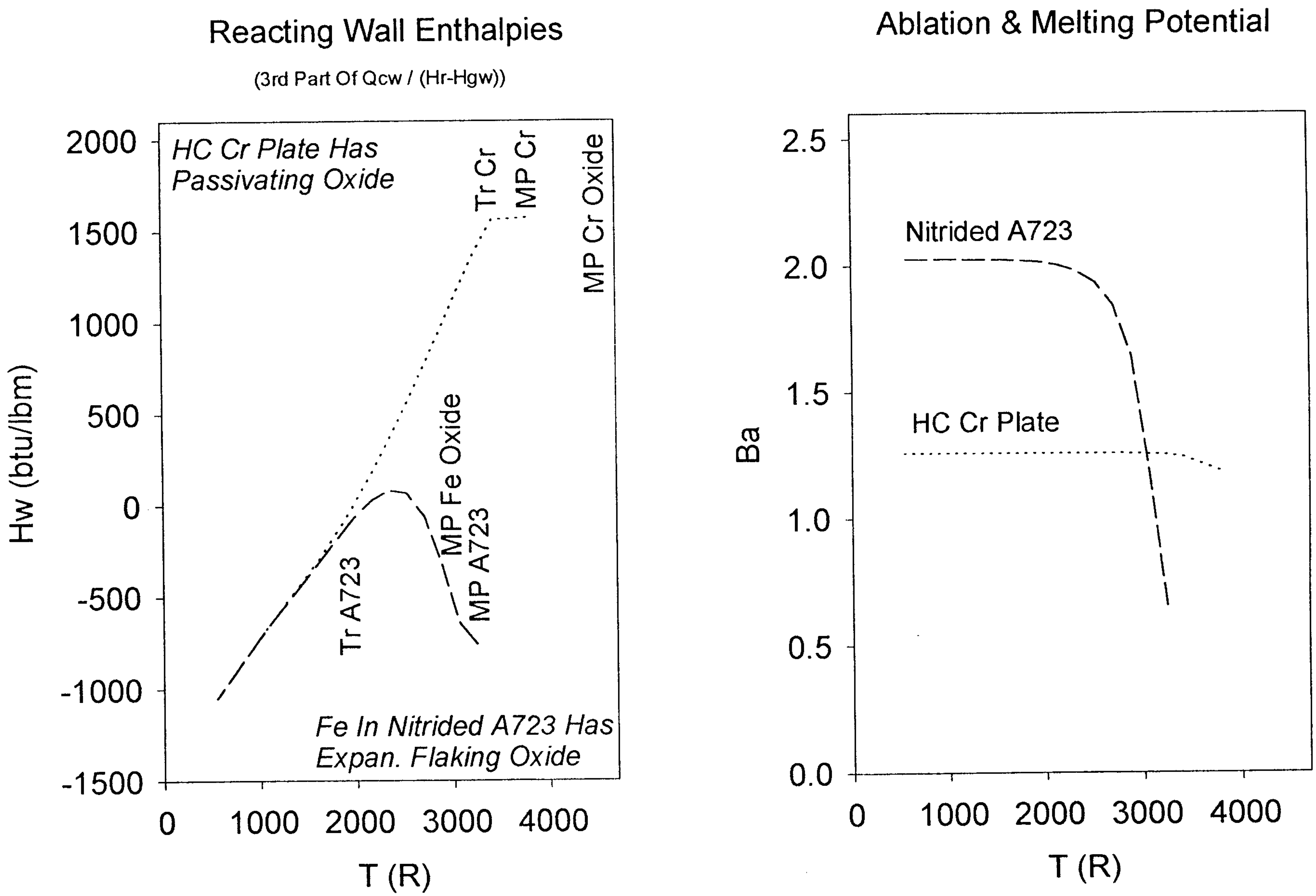


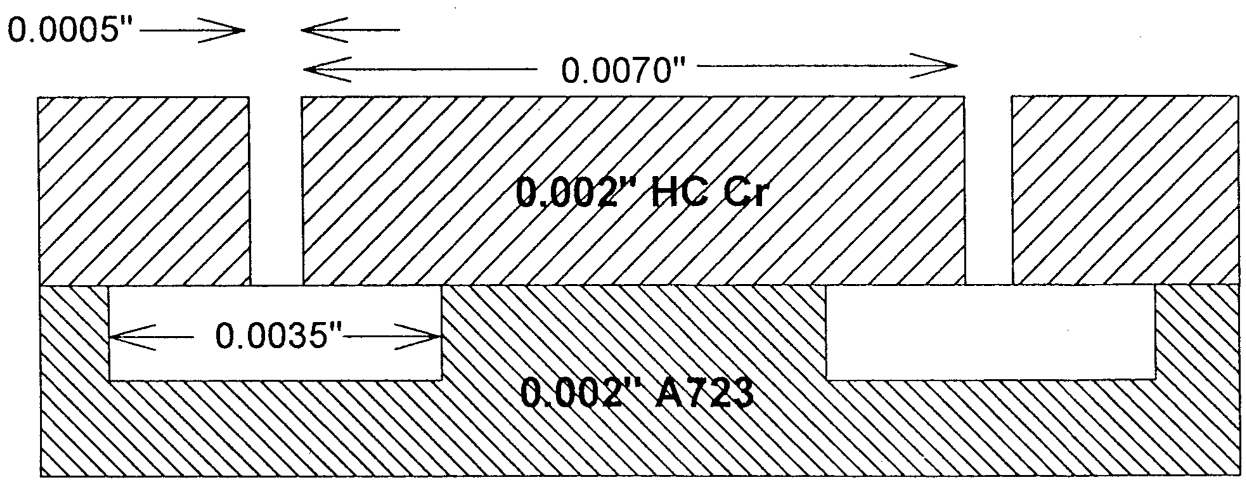
Figure 5 - 25mm M242/M791 6" RFT Surface/Subsurface Exposure & Flow Modeling

100% Of Nitrided A723 Surface
Exposed For TC Ablation

1) Cyclic Thermal Induced Evolution Of Mainly H_2O, O_2, H_2 & Cl_2 Gives HC Cr Shrinkage & Heat Check Cracking

2) HC Cr Achieves "Maximum" Shrinkage/Cracking At ~10% Of Gun's Life For M791 Using Cycle A Firing Scenario

3) A723 TC Gas Wash At Heat Checked Crack Bases & After Platelet Spalling Enhance Mech. Pitting & Chipping



For Last 90% Of Gun's Life,
12% Of A723 Subsurface
Exposed For TC Ablation

Fig. 6 - MACE Ambient Cond. 25mm M242/M791 Max. Wall & Interface Temperatures

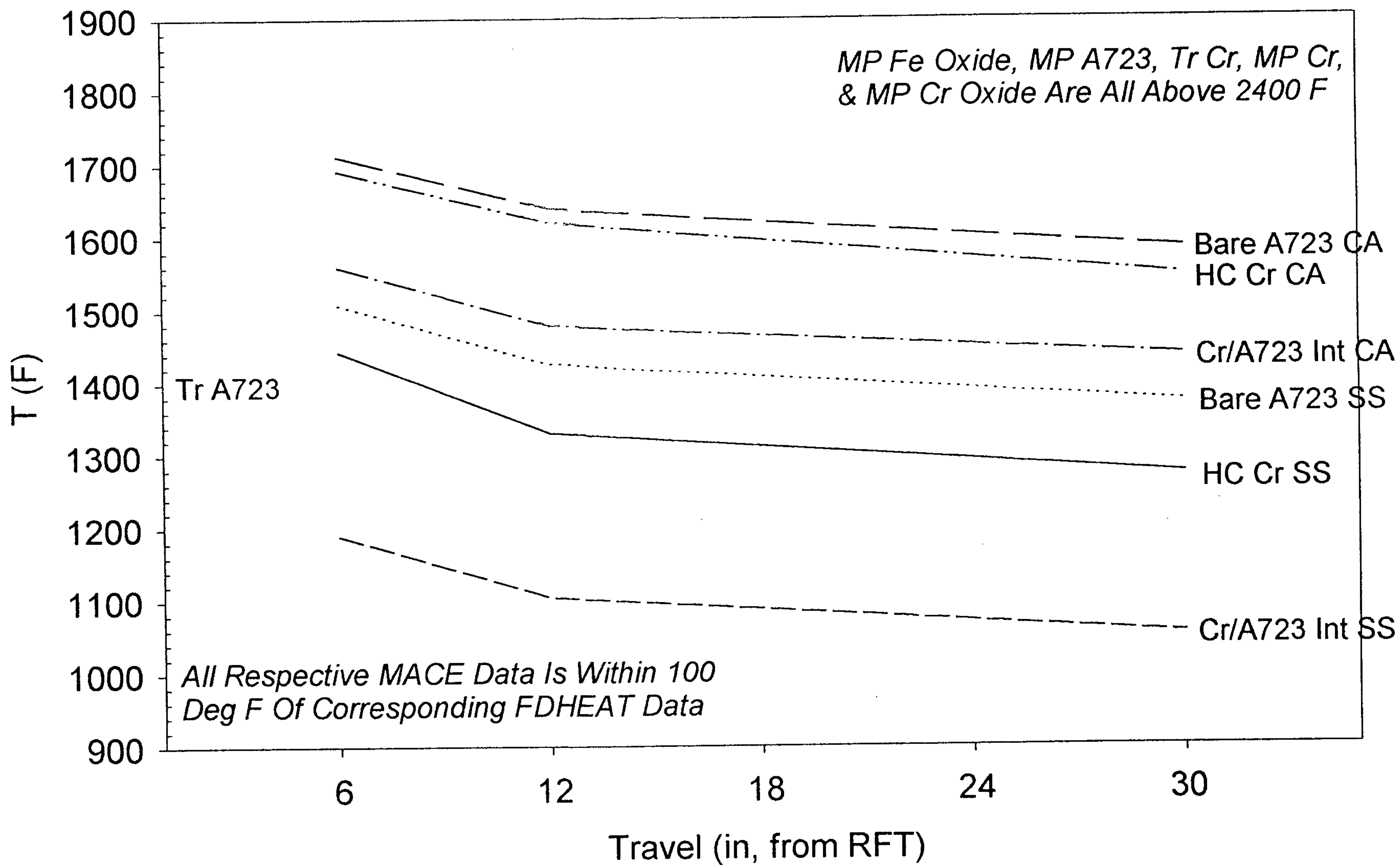
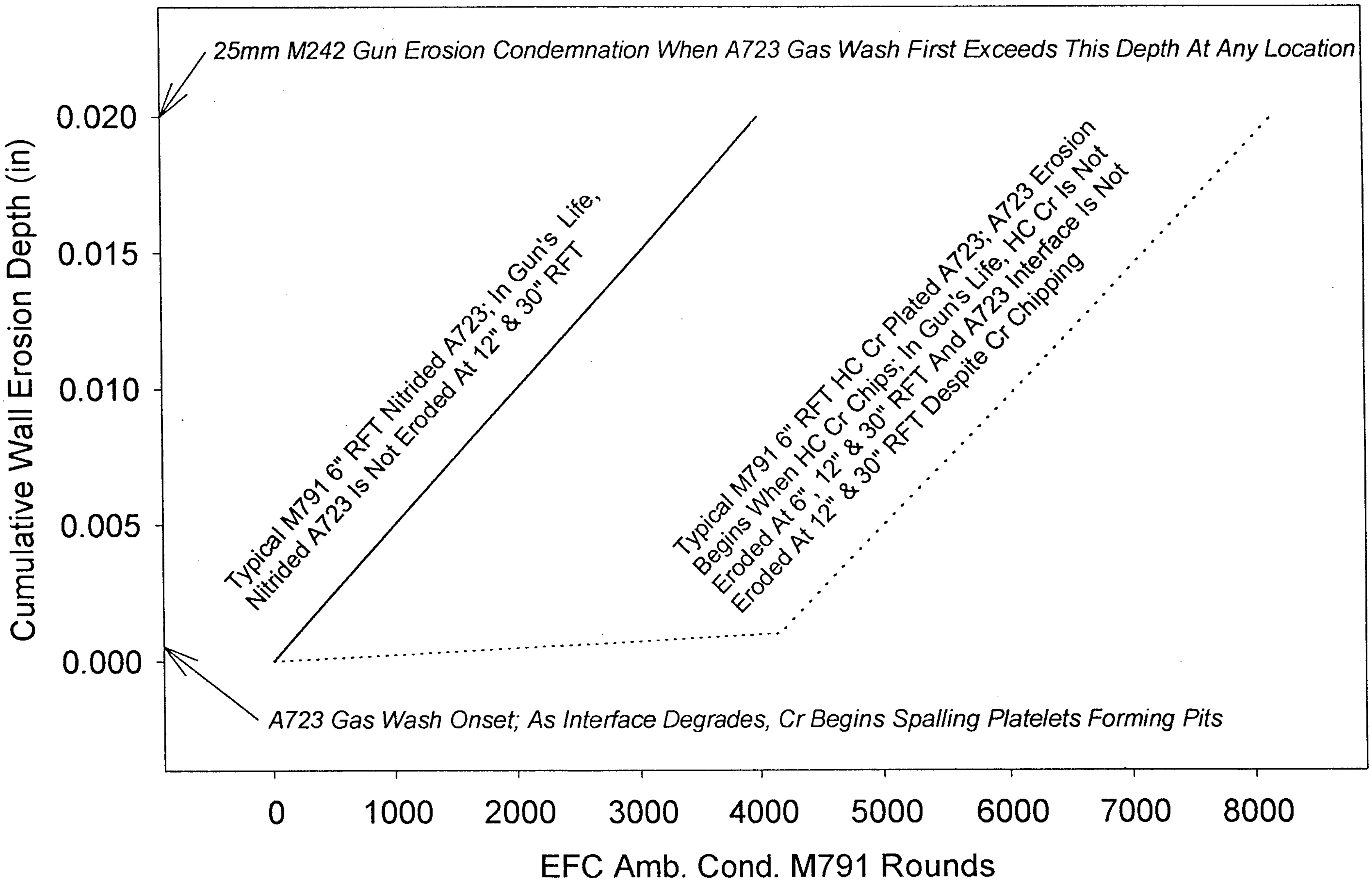


Fig. 7 - MACE Ambient. Cond. 25mm M242/M791 Cum. Wall Erosion To Condemnation



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